GPS IONOSPHERIC SCINTILLATION MEASUREMENTS USING A BEAM STEERING ANTENNA ARRAY FOR IMPROVED SIGNAL/NOISE

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BIOGRAPHY

Dr. Alison Brown is the President of NAVSYS Corporation, which specializes in developing GPS technology. She has over 15 years experience in GPS receiver design and has eight GPS related patents. She is currently a member the USAF Scientific Advisory Board where she supported the New World Vistas, Expeditionary Air Force and Global Air Navigation Services (GANS) summer studies. She is currently chairing the Terrestrial Segment panel for the "Air Force - Going to Space" summer study. She served as the Space Representative for the Institute of Navigation Council in 1993 and has served as the Technical Chairman and General Chairman for the ION Satellite Division and the ION Annual Meetings. She is a member of the editorial board for GPS World.

Dr. Brown received her BA and MA in Engineering from Cambridge University, England, where she was elected as a scholar and exhibitioner of Sidney Sussex college and was awarded the Sir George Nelson prize for applied mechanics. She has a SM in Aeronautics and Astronautics from MIT, where she was awarded the Dupont scholarship and studied as a Draper Fellow. She has a PhD in Mechanics and Aerospace from UCLA.

Eric Holm is an Integrated Product Team leader for the Range and Tracking System group at NAVSYS Corp. He has an MS in Electrical Engineering from the Johns Hopkins University and a BS in Electrical Engineering from the University of New Mexico. He worked at the Applied Physics Laboratory of Johns Hopkins University for 15 years. While at APL he built GPS receivers and analyzed and developed numerous communication systems. He joined NAVSYS Corp. in 1997.

Keith M. Groves received a B.S. degree in physics from Andrews University in 1984 and a Ph.D. in Space Physics from M.I.T. in 1991. Since 1991 he has been on the research staff of the Phillips Laboratory, Geophysics Directorate in Bedford, Massachusetts, where he investigates the interaction of electromagnetic waves with the ionosphere, primarily through radar diagnostics. Specific areas of interest include modification of the ionosphere by high power HF radio waves, the physics of upper atmospheric discharges, and, as the leader of the directorate's scintillation project, the study of irregularity formation in the ionosphere. The goal of these investigations is to assess ionospheric effects on communication and navigation systems.

ABSTRACT

The ionosphere can affect GPS receivers by degrading the signal strength, in some cases causing loss of carrier lock, and by degrading the accuracy of differential corrections. As we enter the solar maximum years, these effects will become more severe, causing frequent GPS outages in the polar and equatorial regions and over the entire North American landmass when magnetic storms occur. These ionospheric anomalies can potentially have a massive effect as more systems, such as nationwide air transportation, are coming to rely on GPS measurements.

A ground monitoring system is being built to detect and characterize these events. To allow ionospheric data to be collected reliably even during large GPS signal fades, a high gain antenna array has been developed and integrated with a digital GPS receiver. An innovative beam steering approach has been implemented using a low cost, PC-based architecture. The array significantly improves the signal/noise ratio for each satellite allowing the receiver to continue tracking even during extreme signal fades caused by scintillation.

This paper describes the beam steering array and digital receiver achitecture used to track the low signal-to-noise GPS signals and presents the results of initial measurements of the array high gain performance.

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INTRODUCTION

Ionospheric activity fluctuates on an 11 year solar cycle. 1995, the year that GPS went operational, was a solar minimum. Over the next 5 years we can anticipate higher levels of solar activity which have the potential to severely affect GPS operation. Because of the widespread use of GPS by the aviation and navigation community, it is imperative that a reliable method be developed for predicting GPS outages under severe environmental effects. The best method of achieving this is through the use of a real-time monitoring network to measure ionospheric fluctuations in total electron content (TEC) and signal amplitude. However, this network must be capable of providing reliable data even during extreme environmental conditions, which requires a high performance ionospheric monitoring ground system.

NAVSYS has developed a high performance GPS antenna and receiver that is capable of tracking the GPS signals down to 10 dB below normal acquisition and track levels (32 dB-Hz). This is achieved through the use of a digital beam steering architecture that applies 10 dBi of gain to the received signal on each GPS satellite. These high gain GPS reference stations are being built under contract to the Phillips Laboratory, Hanscom AFB, and are planned to be used in the equatorial monitoring ground stations that collect ionospheric scintillation observations [1].

IONOSPHERIC EFFECT ON GPS

The ionosphere affects GPS receivers by degrading the signal performance, in some cases causing loss of carrier lock, and by degrading the accuracy of differential corrections. These affects are caused by irregularities of electron density that scatter radio waves at L-band frequencies and generate amplitude and phase scintillation of GPS signals. Amplitude scintillation causes cycle slips and data losses to occur and phase scintillation generates fast variations of frequency with which the receiver has to cope.

The worst source of scintillation is the equatorial anomaly regions. During solar maximum periods, amplitude scintillations may exceed 20 dB for several hours after sunset. Other potentially active regions are at auroral and polar cap latitudes. In the central polar cap in years of solar maximum, GPS receivers may experience >10 dB fades. During times when these fading effects are strong, the refractive effects that produce range-rate errors are also changing, often causing rapid carrier-phase changes. This is the most severe test of a GPS receiver in the natural environment. The doppler shifts caused by TEC variations can be up to 1-Hz/sec which cause some narrow-band receivers to lose lock on the signals.

Magnetic storms will also generate ionospheric anomalies which, although rare, can extend well into the mid-latitudes. For instance, during the March 1989 magnetic storm, during which the aurora extended over most of the continental United States, even higher doppler shifts than 1 Hz/sec were experienced. These anomalies can last over the entire North American landmass for periods of up to one or two days, potentially having a massive effect on nationwide air transportation which will rely on GPS operation for navigation and landing systems.

The occurrence of L-band scintillation at stations at Ascension Island and Huancayo is shown in Figure 1.[2] At Ascension Island, frequently scintillation can cause fade depths in excess of 20 dB. A typical GPS reference receiver will maintain lock down to signal-to-noise ratios of 32 dB-Hz. Normally, the GPS signals can be expected to be above 44 dB-Hz for higher elevation GPS satellites. This means that a conventional GPS reference receiver can only be expected to track through scintillation fades of 12 dB or less. The NAVSYS high gain beam-steering array and GPS reference receiver is designed to apply 10 dBi of antenna gain to each received GPS satellite signal. This enables the NAVSYS GPS reference receiver to track the GPS satellite signals to levels as low as 22 dB-Hz and to tolerate ionospheric scintillation fades as high as 22 dB.

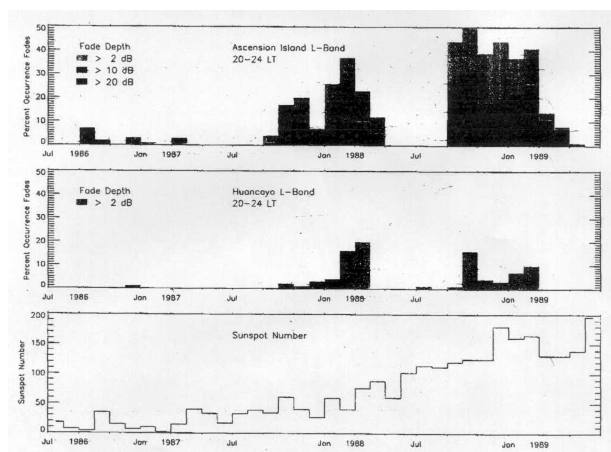

Figure 1 Occurrence Statistics at L-Band Scintillation

HIGH GAIN GPS REFERENCE RECEIVER DESIGN

The high gain ionospheric monitoring GPS reference receiver design is based on NAVSYS' Advanced GPS Receiver (AGR) PC-based digital receiver architecture[3], integrated with a digital beam steering array. Using a proprietary digital signal processing algorithm NAVSYS is able to combine data from as many as 16 antennas and create a multi-beam antenna pattern to apply gain to up to eight GPS satellites simultaneously. In Table 1, the performance specifications for NAVSYS beam steering array and AGR receiver are shown for different antenna

array configurations. The AGR receiver specification is shown in Table 2.

Table 1 Digital Antenna Array Gain

#Antenna Elements	Ideal	Spec
2	3 dB	2 dB
4	6 dB	5 dB
9	9 dB	7 dB
16	12 dB	10 dB

The high gain GPS reference receiver design consists of the components shown in Figure 1. A multi-element antenna array is assembled using commercial antenna elements. The antenna outputs are fed to a Digital Front End (DFE) assembly which includes a custom RF-board that digitizes each of the received L1 signals. The digital output from the DFE assembly is then passed to a custom Digital Beam Steering (DBS) board installed in the AGR Personal Computer that performs the digital signal processing required to implement the digital beam steering operations. The AGR PC also includes a custom Correlator board that performs the C/A code correlation and carrier mixing on each satellite channel.

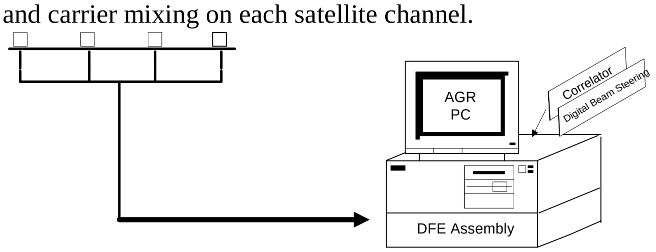

Figure 2 High Gain GPS Reference Receiver Design

Depending on the level of performance desired, the antenna array and DFE assembly can be populated with two, four, nine or sixteen antenna elements. The antenna array configurations and are shown in Figure 2. The antenna elements are spaced ½ wavelength apart.

The Digital Beam Steering board is operated through software control from the AGR PC. This applies the array DSP algorithms to form the digital antenna array pattern from the multiple antenna inputs, adjusts the antenna array pattern to track the satellites as they move across the sky, and applies calibration corrections to adjust for offsets between the individual antenna and DFE channels and alignment errors in the positioning of the antenna elements and array assembly.

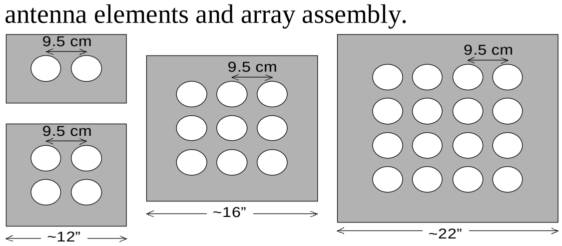

Figure 3 Alternative Antenna Array Configurations

Table 2 AGR Performance Specifications

Technical Specifications	
GPS Frequency	L1, 1575.42 MHz
Source	C/A code (SPS)
Channels	8 channels
Correlation	Adjustable Spacing
Operating Specifications	
Peak Vehicle Dynamics	
Velocity	10,000 m/sec
Acceleration	100 g
Jerk	100 g/sec
Position Update Rate	1-1000 Hz
Raw Data Output Rate	1-1000 Hz
Time To First Fix	40 secs (cold – no time or position)
Re-Acquisition	10 secs to valid position
DFE Input Signals	
Center Frequency	1227.6 to 1575.42 MHz
Nominal Signal Level	-136 to-86 dBm
Signal Bandwidth	0 to 20 MHz
CW or Noise Interference Levels at DFE Input	
Center Frequency ± 10 MHz	10 dB above weakest
1200 to 1600 MHz	<-80 dBm
Outband Interference	<-20 dBm
Built-in Modules	DGPS (reference and remote) Timing Reference
DFE Output Signals	
Digital Samples	I, Q, or I&Q
A/D	1-4 bits
Sample Rate	2-25 MHz
IF Frequency	70 MHz
User Configuration Parameters Selectable through configuration file or user interface	Vehicle Dynamics Track Thresholds DLL and PLL or FLL bandwidths and thresholds DFE characteristics Correlator spacing Data logging rates Satellite selection methods

The AGR provides the ionospheric output data at a rate which is selectable from 1 Hz to 50 Hz. The output data includes the observed signal-to-noise (C/No) and the carrier phase. The data is output to a file that can be shared with a web server connected to the Internet. The data can be remotely read over the Internet enabling data collection at remote sites.

ANTENNA ARRAY BEAM PATTERNS

The beam pattern created by the digital antenna array is a function of the number of elements used in the array and the elevation angle of each satellite being tracked. In

Figure 3 a typical beam pattern to a single GPS satellite is shown for a 16-element array.

HIGH GAIN GPS REFERENCE RECEIVER TEST DATA

A two element array has been tested using real satellite signals. The increased C/No that results from combining the two elements is shown in Figure 5 and 5. The plots are broken into three time segments. In the first and third segments, the C/No for the individual elements is shown. This gives a baseline C/No measurement for the given satellite, antenna, and front end. In the middle time segment, one trace shows the C/No for antenna 0 and the other trace shows the C/No for the combined antenna elements. For the combined trace, the phases on the two elements were adjusted to point a beam at each satellite. The trace of the combined antenna elements clearly shows a 2.5 to 3 dB gain for both of the satellites being tracked by the array. Ideal is 3 dB for a two element array.

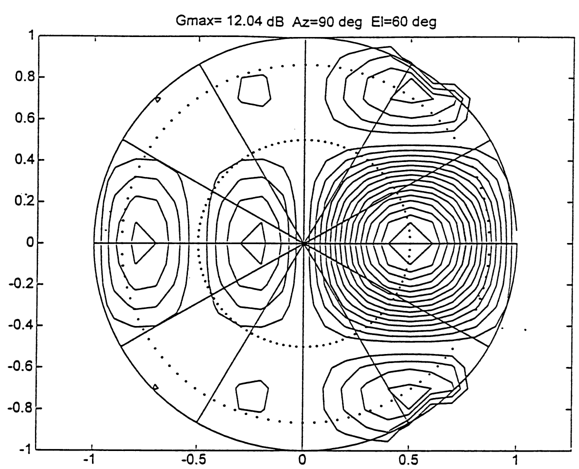

Figure 4 Single Satellite 16-element Digital Array Beam Pattern

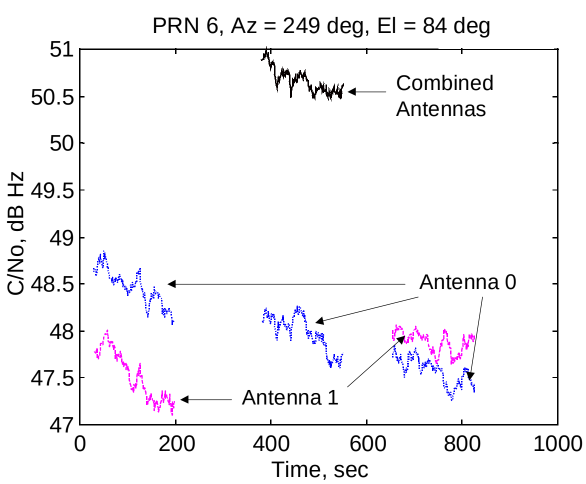

Figure 5 Two element array test-data (PRN6)

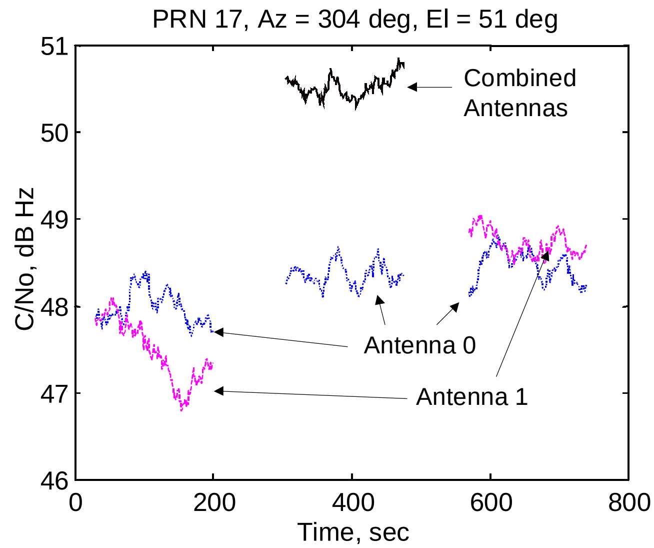

Figure 6 Two element array test data (PRN17)

CONCLUSION

In this paper, the design, performance and test results of the NAVSYS high gain digital beam steering array and GPS receiver have been presented. The benefits of the high gain GPS reference receiver for the following applications are summarized below.

<u>Ionospheric Monitoring</u>
The high gain antenna array enables the NAVSYS receiver to track GPS signals down to 22 dB-Hz signal-to-noise ration. This enables the NAVSYS reference receiver to continue to provide ionospheric test data from GPS satellites through scintillation signal fades in excess of 20 dB.

<u>Differential Reference Station'</u>
The gain applied to the GPS signals by the antenna array improves the signal strength observed in the tracking loops by up to 10 dBi (for the 16-element array option). This will improve the pseudo-range residual noise from the AGR's delay lock loops by a factor of 3. The improved pseudo-range accuracy results in higher precision in differential corrections generated by this reference receiver.

<u>Multipath Rejection</u>
The antenna array digital signal processing algorithms applied by the programmable Digital Beam Steering (DBS) PC-board can be optimized to reject satellite signals received at low elevations. This attenuates any multipath signals received while applying gain to the direct path GPS satellite signals. The combination of these effects is to significantly reduce the residual multipath error in the AGR's delay lock loops.

Interference Rejection

The antenna array digital signal processing algorithms applied by the programmable DBS-board can be programmed to apply nulls as well as generate gain through forming beams. By placing nulls on interfering signals, the DBS-board can also be used to reject interference sources or signals from GPS jammers.

ACKNOWLEDGEMENT

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